DEVELOPMENT OF A CONSTITUTIVE LAW FOR A 5-15 KM SCALE IN THE ARCTIC ICE PACK

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Award No. N00014-96-C-0299

LONG TERM GOALS

Develop a basis for relating differential pack ice motion to the resulting stress variations within floes on scales of the order of 5-15 km. Use such relationships to develop a constitutive law relating strains to stresses in pack ice to be utilized in the next generation, high resolution, forecasting models for high latitude regions.

OBJECTIVES

Study motion-induced stresses in pack ice through the analyses of a variety of observations collected during the Sea Ice Mechanics Initiative. Investigate the relationships between observed differential ice motion over the scales of 5-15 km and the observed residual (internal) stresses within floes in an attempt to develop a rheology relating strain in the ice pack to internal stresses within individual floes.

APPROACH

To directly assess the mechanical behavior of the Arctic pack ice at regional scales, the Office of Naval Research (ONR) initiated a program of concurrent measurements of in-situ ice stresses and ice motion during the recent Sea Ice Mechanics Initiative (SIMI). A stress and deformation array was established over a 20 km region of the pack ice in the Alaskan Beaufort Sea, and measurements were recorded over six months, beginning in September 1993. To develop a more detailed understanding of the relationship between observed stresses and ice pack deformation, we focused on the characteristics of the observed motion-induced stresses. Since stresses in a floe result from both thermal as well as motion-induced processes, a technique had to be developed to estimate those stresses due strictly to ice motion. With a satisfactory estimate of the motion-induced stresses in hand, a number of techniques was used to develop an understanding of how these stresses are generated. These techniques include a comparison of the measured stresses to those stresses determined as residuals from a force-balance analysis using SIMI wind, under-ice current, and ice motion data. The characteristics of the stresses determined from the force-balance analysis are described as they relate to the observed motion-induced stresses and the differential motion of the floes in the SIMI region. Finally, numerical simulations are used to investigate the complex distribution of motion-induced stress within a multi-year floe.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 1997**	2. REPORT TYPE	3. DATES COVERED **00-00-1997 to 00-00-1997**

4. TITLE AND SUBTITLE **Development of a Constitutive Law for a 5-15 Km Scale in the Arctic Ice Pack**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Ocean Physics Research & Development,207 S. Seashore Ave,Long Beach,MS,39560**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

ACCOMPLISHMENTS

Stress gauge observations from three locations on the main SIMI floe were considered for a 25 day period during 1993. Along with these data, we compiled data on wind and under-ice current forcing and the movement of seven floes. The stress gauge data were processed to obtain estimates of motion-induced stresses at the three locations on the main SIMI floe. Independently, the wind, current, and motion data were used to estimate the mean internal stress throughout the main SIMI floe based on the momentum balance equations for pack ice. These mean internal stresses were then compared with the motion-induced stress from the gauge data. Assuming both are a reflection of the same forcing, horizontal scales over which the forcing was distributed were determined by scaling one set of stresses to the other.

The ice motion observations were used to calculate differential ice motion in terms of divergence, vorticity, normal deformation, and shear deformation. These were studied to assess the relationship between ice deformation and the occurrence of motion-induced stresses seen in the main SIMI floe. In addition, a numerical model was generated to simulate the structure of motion-induced stresses within a nearly circular floe. The structure of the internal stress fields generated by compression as well as shear along the edges of the floe were determined numerically. These results were used to assist in our understanding of observed motion-induced stresses at various locations within a floe relative to the forcing at the edges of the floe.

SCIENTIFIC/TECHNICAL RESULTS

Our study concentrated on understanding motion-induced stresses within typical floes in the Arctic. We produced our best estimates of the motion-induced components of stress from stress gauge data collected at the main SIMI floe. These estimates are in terms of force per unit vertical area. We then applied a force balance argument and used wind, current, and ice motion data to calculate the net motion-induced stresses for the main SIMI floe. The calculated residual stresses are in terms of force per unit horizontal area. Of three significant stress events determined by the force-balance calculations, only the one event in the north-south direction had a strong corresponding signal in the stress gauge data. The strongest residual stress event was an east-west event, and there is very little indication of this stress event in the gauge data. The calculated residual stresses were then converted to force per unit vertical area and compared to the estimates of motion-induced stresses from the gauge data (Fig. 1). To do this, we had to pick a horizontal width over which the residual stresses were distributed. In the north-south direction, a width of 10 m produced a good reproduction of our estimates of the motion-induced stresses. In the east-west direction, the width chosen was 50 m. This larger width reduced the signature of the residual stress to the order of the variations of the motion-induced stresses seen in the gauge data. Together, these results suggest that, in many instances we may have significant and dynamically important motion-induced stresses within a floe overall, but the magnitude of the stress at a given location within the floe can vary substantially depending on the region over which the stress is distributed.

The results also provided some insight into the so-called “ridge-building” force used in sea ice models. In most models, the strength of the pack ice within a grid cell is referred to as the ridge-building force since ridge building is assumed to occur if the stress attempts to exceed this strength criteria. The ridge-building force used in many Arctic sea ice models reflects the net strength of a large region of pack ice (scales of the order of 100-125 km), and this has been determined to be about 25-30 kPa based on matching model velocities to observed ice drift. However, stresses measured by sensors close to actual ridge-building events tend to be at least an

order of magnitude larger than 25-30 kPa. So there is quite a discrepancy between the values of the ridge-building forces we use in models and those we actually observe from point stress measurements at ridge-building sites.

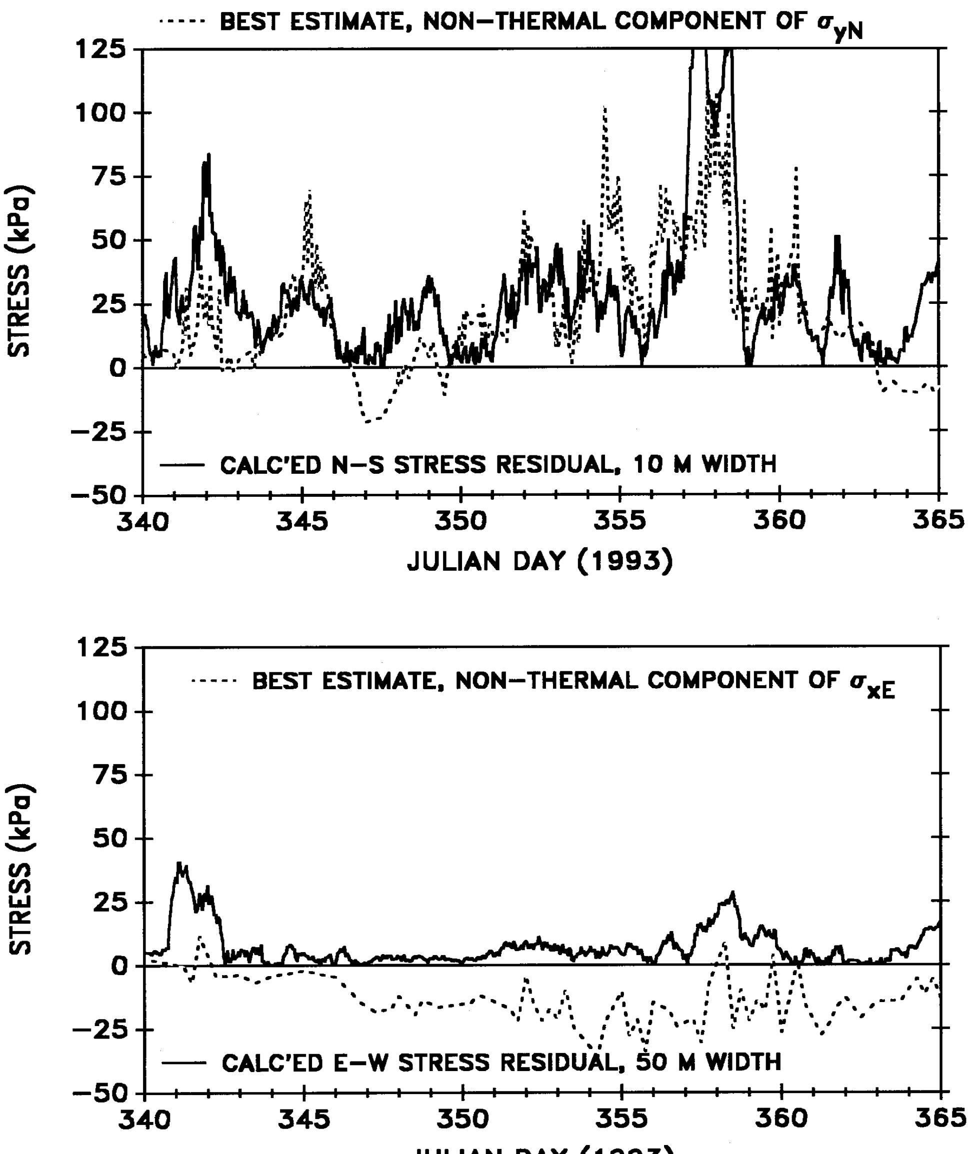

Fig. 1. Comparisons between the calculated residual stress and gauge stress in the north-south direction based on a 10 m Δx (top) and the calculated residual stress and gauge stress in the east-west direction based on a 50 m Δy (bottom).

We can evaluate this discrepancy using the residual stress calculations. The calculations give us events with maximum magnitudes of ~0.4 Pa for an average ice thickness of 1.42 m. If we were working with an ice model with grid cells of the order of 100-125 km, a 0.4 Pa stress in terms of force per unit horizontal area would represent ~28-35 kPa of stress in terms of force per unit vertical area. This is approximately equal to the 25-30 kPa that is used in many Arctic sea ice models as the ridge-building force. However, this conversion of a 0.4 Pa maximum to 28-35 kPa ridge-building force assumes that the 0.4 Pa stress event is distributed over the entire length of the side of a model grid cell (100 km in the above example). Our analyses indicate that, in reality, the distribution may be over a smaller length, which can increase the stress at a given site and might actually result in ridge building. For example, for an ice model with a grid with the same volume of the SIMI floe (3 km diameter, 1.42 m thick), a maximum magnitude of 0.4 Pa when distributed over the entire 3 km would convert to a "ridge-building" force of only 0.7 kPa in terms of force per unit vertical area. Yet the corresponding event in the gauge data has a signature in the gauge data of ~100 kPa. According to our analysis, this residual stress (order of 0.2 Pa) would be acting over a horizontal length of only ~10 m, not the larger horizontal scale of a grid with the same volume of the SIMI floe. A force of 100 kPa conceivably could have resulted in some rafting or ridge-building within the SIMI region, so, if we were modeling the region with a grid with the same volume of the SIMI floe, we would have to set the ridge-building force to ~0.7 kPa. Thus, the discrepancy between the magnitudes of actual ridge-building forces and a model "ridge-building" force is really just be a matter of having to work with the scale of the grid in the model.

The principle result of the numerical simulation of the distribution of motion-induced stresses within a floe is that the character of a motion-induced stress events is not only dependent on the area over which the stress is distributed but also the location in the floe at which observations are made. Altogether, these simulations suggest the possibility that the seeming lack of a clear correspondence in the signature of the stress gauge data to two of the three major residual stress events *may not* be a result of the distribution of the force over a relatively large area. Instead, the lack of correspondence in the measured and calculated stress may simply be due to the difficulties of interpreting the local point measurements of stress in a system that exhibits significant horizontal spatial variability. As seen in Fig. 2, if the stress event was caused by shearing stresses, the signature of the event could range from compression to practically zero stress to tension, all depending on the location of the observations relative to the forcing.

Although our study has provided us with a far better understanding and signatures of motion-induced stresses within a floe, we still lack the knowledge of how to relate the variations of our residual stress with the differential motion as seen by the cluster of drifters on different floes. We have considered a number of plausible formulations relating the calculated residual stress variations to the observed strain rates, but we have been stymied by the fact that convergence of the ice pack does not always correlate with increasing residual stresses. While the three main events seen in the residual stresses all occurred during ice pack convergence, based on the formulations we have tested so far there also should have been some significant stress events during two other periods as a result of the substantial convergences of the ice pack during those times.

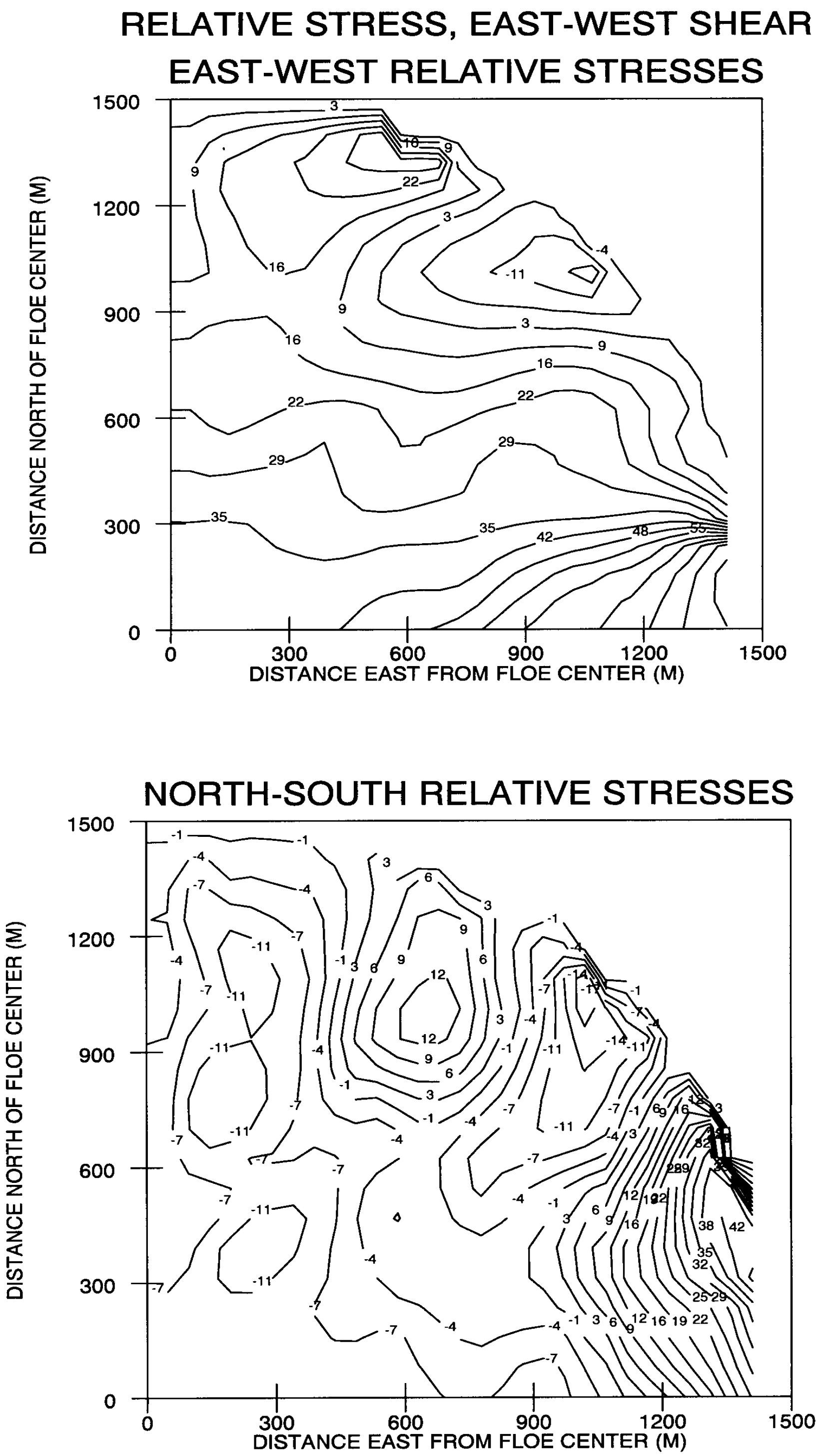

Fig. 2. Relative compressive (positive) and tensile (negative) stresses in the x direction (top) and y direction (bottom) for the upper left quadrant of a nearly circular floe being forced with a shearing strain rate of 10^{-6}/s. All stresses have been scaled by the maximum compressive stress which occurs at the bottom right corner and multiplied by 100.

Obviously, the relationships between the residual stress in the ice pack and the differential motion of the floes needs additional research and study. However, our results point out the possibility that the residual stresses might not be generated by local deformation of the ice. Perhaps the residual stress was transferred through the ice pack from a remote site, a process that can only occur when both 1) the ice has converged sufficiently across the pack to propagate the stress from a remote site and 2) there exists a stress at a remote site to propagate. This elastic transmission of stress is another factor to be considered in our continuing study of motion-induced stresses in pack ice.

Overall, our results add further confirming evidence that the process of stress transmission through the ice pack during periods of ice motion over scales of meters to 10's of kilometers is extremely complex. We have seen that some non-thermal events seen in the stress gauge observations could be related directly to the residual stresses determined from the balance of forces acting on the SIMI floe. However, other significant and dynamically important stress events were not discernible in the stress gauge observations. Our analyses indicate that the detection of stress events by a given stress gauge will be determined by 1) the location of the stress gauge relative to the location of the forcing on the floe and 2) the horizontal distance over which the stress event is distributed in the floe. Compressive forcing and, in particular, shearing forcing at the edge of a floe can result in complex patterns of stress throughout the floe, making the assessment of motion-induced stresses from individual gauge data a difficult task. Furthermore, we have found that there is not a logical formulation by which the stress events determined from the force balance equations can be related to the differential motion of the ice surrounding the SIMI floe. It is possible that, even for those motion-induced events that can be readily discerned from stress gauge observations, the forcing may be far-field, not local. On the other hand, we must consider the possibility that the strain rates calculated using the surrounding ice drift data were not those actually acting along the edges of the SIMI floe. In other words, the stain data were not "local" enough, and we should have made direct observations of the interactions along the boundaries of the SIMI floe.

IMPACT FOR SCIENCE/ SYSTEMS APPLICATIONS

Studies related to the development of the next generation forecasting capability for high latitude regions (ONR, Naval Ocean Modeling Program).

RELATED PROJECTS

None.

PUBLICATIONS

Lewis, J. K., 1997: Thermal stressing of pack ice. In *Proc. of the 7th Int'l. Offshore and Polar Eng. Conf.*, Honolulu, May 25-30, 1997. Int'l. Soc. Offshore and Polar Eng., 394-401.

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